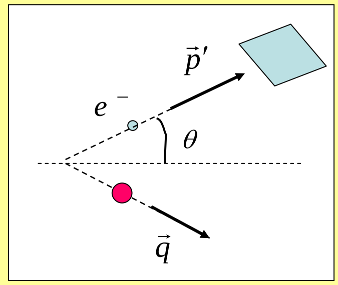
Inelastic scattering refers to the process in which energy is transferred to the target, exciting internal degrees of freedom.

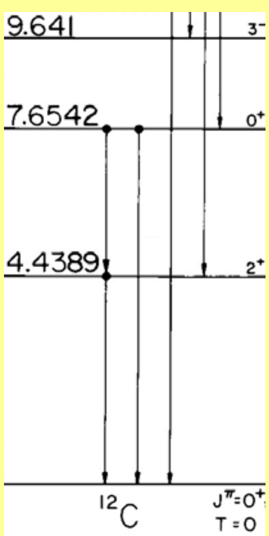
Experimental Scenario:

- Electrons are detected in a spectrometer set at angle θ
- The momentum of the scattered electrons at given θ depends on whether they scatter elastically or inelastically
- Peaks in the cross-section for inelastic scattering correspond to excitation of higher energy states in the target.
- Good resolution in the scattered electron momentum measurement is important to be able to resolve the energy spectrum of the target particle.



Example: Early days at SLAC, inelastic scattering from Carbon

R. Hofstadter, Rev. Mod. Phys. 28, 214 (1956)



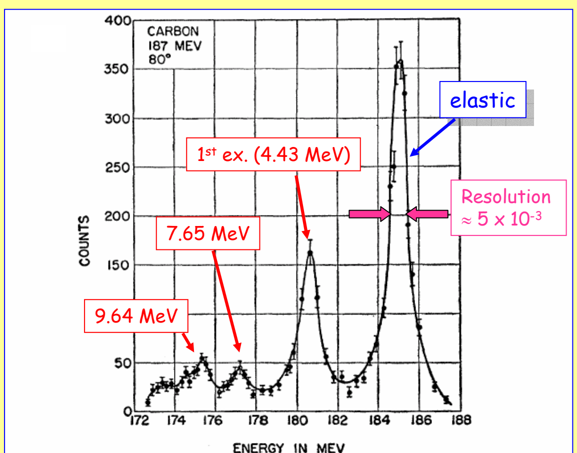


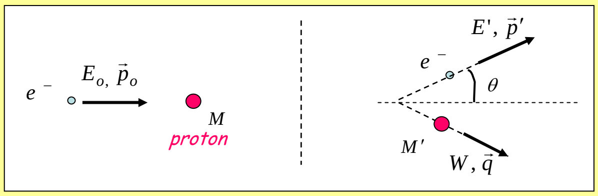
FIG. 11. The elastic scattering peak from carbon near 185 Mev and the inelastic scattering peaks from excited states of carbon. The peak near 180.7 Mev is associated with the 4.43-Mev level.

Scattered electron momentum = energy; energy loss by e- is gained by the recoiling ^{12}C

Kinematics for inelastic scattering:

3

- Essential point: the **mass** of the recoiling particle is greater when it absorbs energy from the electron beam.
- Total energy of the recoil particle is: W = M' + K = (M + ΔE) + K where ΔE is the internal energy transfer (excitation energy).



conserve energy and momentum....

$$E_o + M \;=\; E' + W \;=\; E' + M + \Delta E + K, \qquad \vec{p}_o = \vec{p}\,' + \vec{q}$$

Square the momentum equation, use relativistic relation of K to p ....

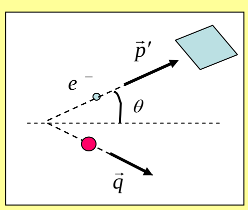
$$p' \;=\; \frac{p_o - \Delta E - \frac{\Delta E^2}{2M}}{1 + \frac{p_o}{M}(1-\cos\theta)} \;\cong\; p_o - \Delta E \quad \text{for large M}$$

Check that this works for the old ^{12}C data:

4

$$p' \;=\; \frac{p_o - \Delta E - \frac{\Delta E^2}{2M}}{1 + \frac{p_o}{M}(1-\cos\theta)} \;\cong\; p_o - \Delta E \quad \text{for large M}$$

187 MeV beam



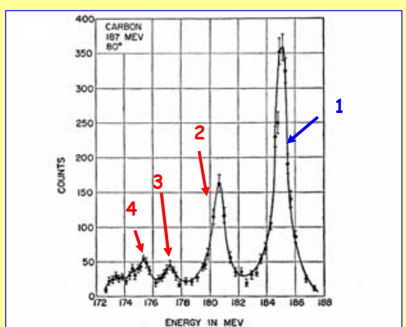
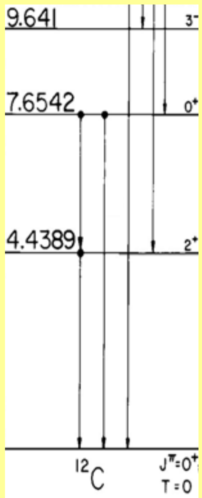


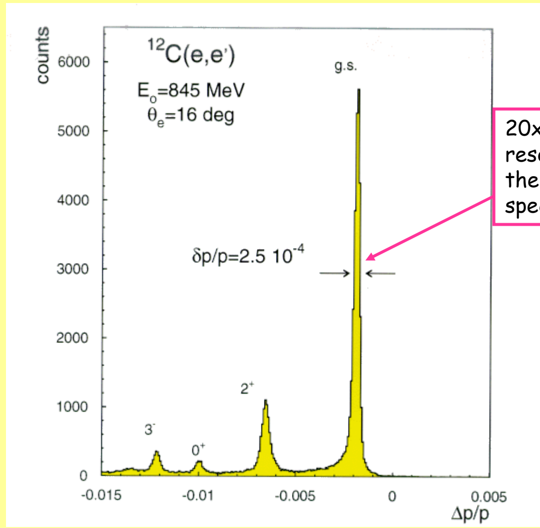
Fig. 11. The elastic scattering peak from carbon near 185 Mev and the inelastic scattering peaks from excited states of carbon. The peak near 180.7 Mev is associated with the 4.43-Mev level.

Peak	cp' (MeV)	dE (MeV)	12-C level
1	185	0	ground state
2	180.7	4.3	4.44 MeV
3	177.2	7.8	7.66 MeV
4	175.2	9.8	9.64 MeV

Energy loss in target: 2 MeV (few mm thick)

Modern High Resolution data from Jefferson Lab, Hall A: 5

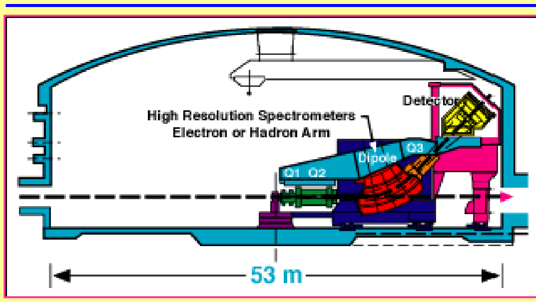




20x better resolution than the old SLAC spectrometer

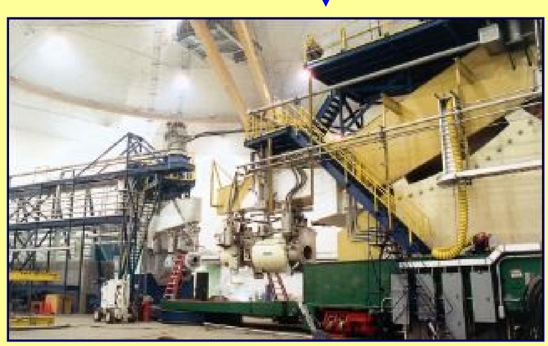
What are we looking at?

Electrons are tracked in a high resolution magnetic spectrometer ... 6



Jefferson Lab "Hall A"

p_o <= 5.9 GeV

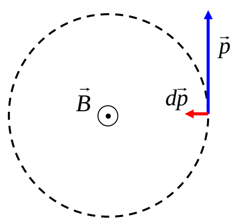


for more information and photos:

http://education.jlab.org/sitetour/

Analysis: deflection of electrons in a magnetic field

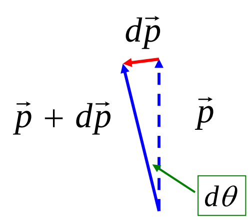
7



Lorentz force:

$$\boxed{\vec{F} = -e\,\vec{v}\times\vec{B} = \frac{d\,\vec{p}}{dt}}$$

(correct, with relativistic momentum — see Griffiths "Introduction to Electrodynamics")



Deflection $\Delta\theta$, even if B is not uniform:

$$d\vec{p} = -e\,(\vec{v}\,dt)\times\vec{B} = -e\,d\vec{\ell}\times\vec{B}$$

$$d\theta = \frac{dp}{p} = \frac{e}{p}\,B\,d\ell$$

$$\Rightarrow \boxed{\Delta\theta = \frac{e}{p}\int B\,d\ell}$$

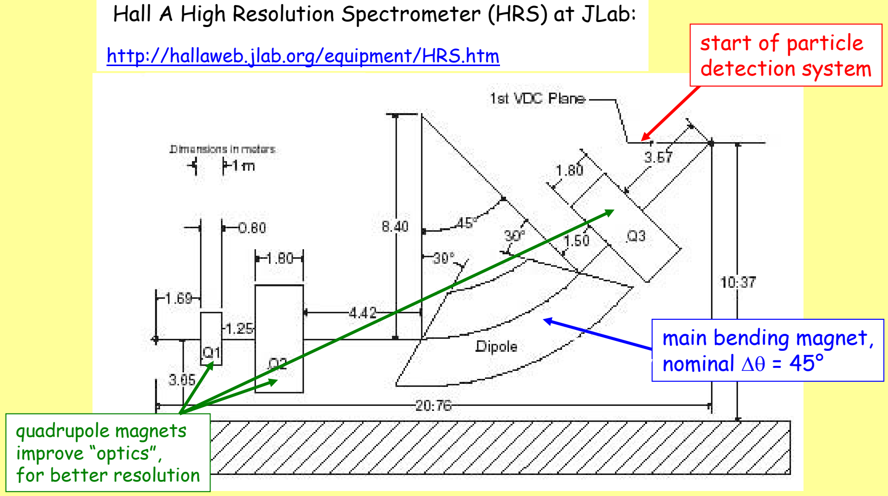
Deflection in magnetic field measures the particle's momentum!

8

$$\boxed{\Delta\theta = \frac{e}{p}\int B\,d\ell = \frac{const.}{p} \quad \text{for central trajectories}}$$

Hall A High Resolution Spectrometer (HRS) at JLab:

http://hallaweb.jlab.org/equipment/HRS.htm



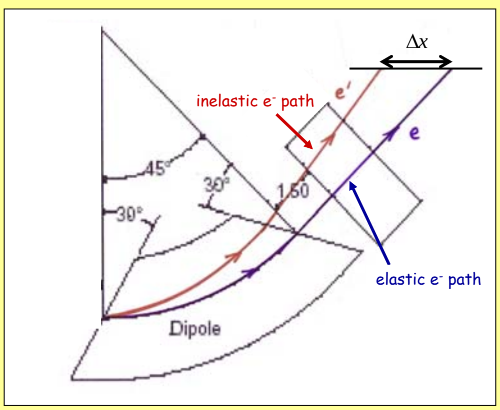
Properties of the Hall A "HRS" spectrometer:

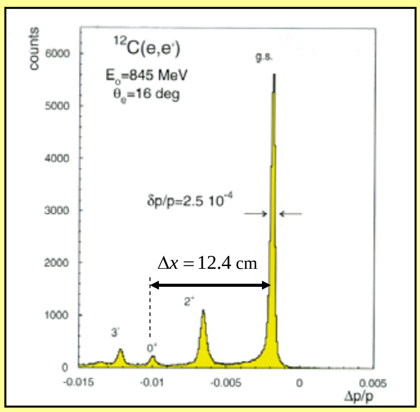
9

Momentum Range	0.3 – 4.0 GeV/c
Magnet configuration	QQDQ
Bend angle	45°
Optical length	23.4 m
Momentum acceptance	± 4.5 %
Dispersion (D)	12.4 cm/%
Momentum Resolution (FWHM)	1×10^{-4}
Acceptance: Horizontal Vertical	 ± 28 mr ± 60 mr
Solid angle (rectangular approx)	6.7 msr
Angular resolution Horizontal Vertical	 0.6 mr 2.0 mr
Transverse length acceptance	± 5 cm
Transverse position resolution	1.5 mm (FWHM)
Spectrometer angle position accuracy	0.1 mr

Position shift of inelastic peaks at the focal plane determines their momentum:

10





Dispersion: D = 12.4 cm/ %

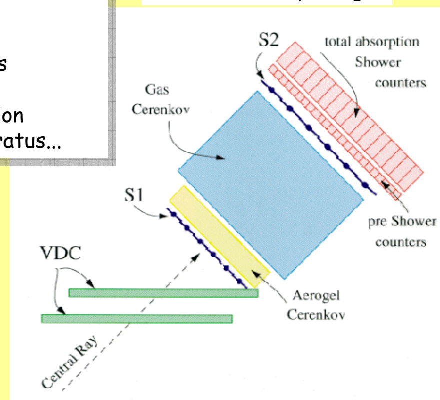
→ A 1% shift from the central momentum corresponds to a deflection at the focal plane of 12.4 cm **more** than the elastic peak.

Experimental requirements:

- accurate position-sensitive detector package
  ("vertical drift wire chambers" VDC)
- accurate spectrometer field map for particle tracking
  (numerical fitting algorithm)
- fast timing scintillation detectors to define events
- Cerenkov detectors for particle identification
  (fire on electrons only to reduce background)
- accurate position/angle survey of components
- "thin" detector packages to minimize resolution smearing caused by scattering in the apparatus...

Picture show, courtesy of Jefferson Lab web page

HRS detector package:

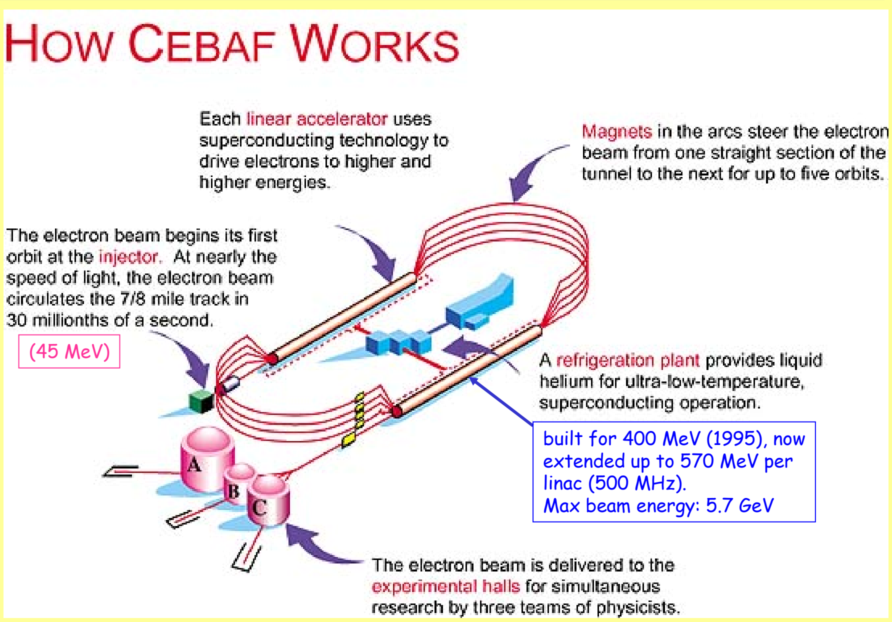


JLab Hall A HRS: *(state of the art)*

positioning error: $\Delta\theta = 0.1$ mr

resolution: $\delta\theta_x = 0.6$ mr *(momentum direction)*
$\delta\theta_y = 2.0$ mr

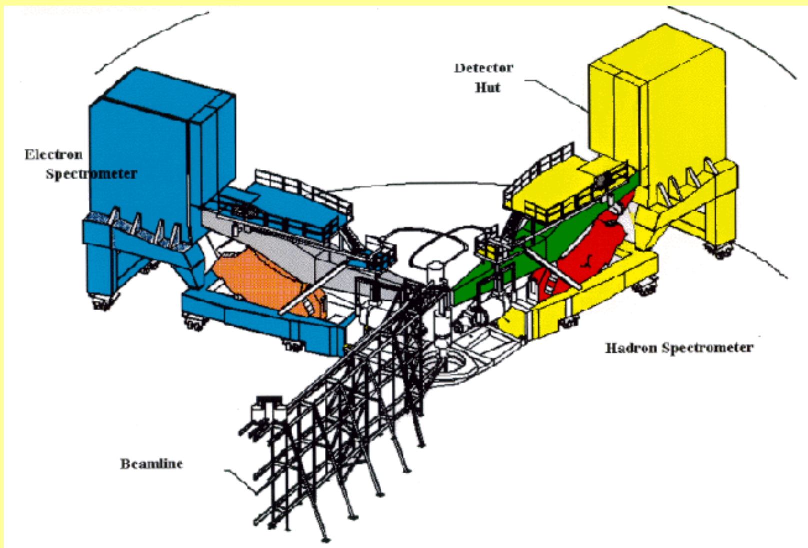
Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab, USA



(45 MeV)

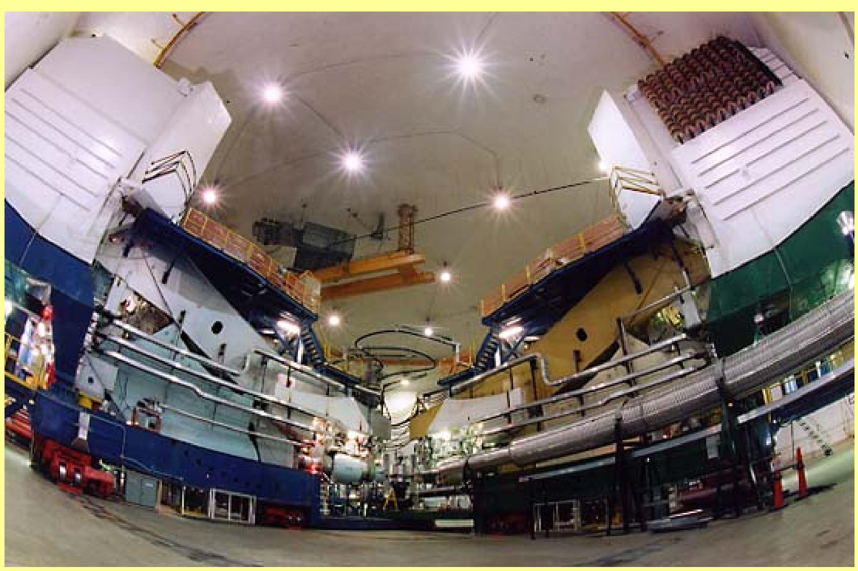
built for 400 MeV (1995), now extended up to 570 MeV per linac (500 MHz).
Max beam energy: 5.7 GeV

Two spectrometers! One for electrons and one for scattered protons, etc. 13



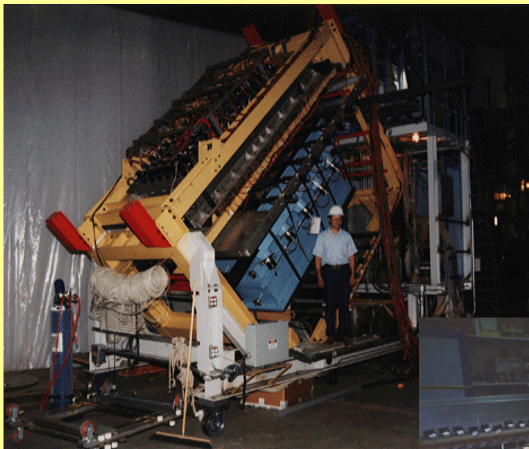
Experimental Hall A at Jefferson Lab

Here they are, but not without some distortion from the camera lens... 14



Some of the electron-arm detection equipment:

15



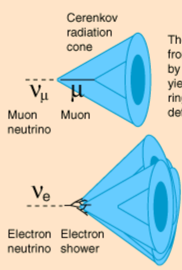
Electron arm detectors:
Cerenkov cell (blue)
shower counters behind...

Assembly of position-sensitive vertical drift chamber (VDC)

Cerenkov Radiation

16

When highly radioactive objects are observed under water, such as in "swimming pool" reactors and in the underwater temporary spent fuel storage areas at nuclear reactors, they are seen to be bathed in an intense blue light called Cerenkov radiation. It is caused by particles entering the water at speeds greater than the speed of light in the water. As the particles slow down to the local speed of light, they produce a cone of light roughly analogous to the bow wave of a boat which is moving through water at a speed greater than the wave speed on the surface of the water. Another analogy statement is to say that the Cerenkov cone is like a sonic boom except that it is done with light.

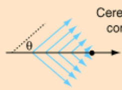


The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.

One of the valuable applications of Cerenkov radiation is in the detection of neutrinos and distintinguishing between different types of neutrinos. An energetic muon remains intact while slowing down and its Cerenkov cone paints out a well-defined circular ring on the detector array. A high energy electron on the other hand will produce a diffuse ring on the detectors because it will produce a shower of electrons, each with its own Cerenkov cone.

Measurements of particle speeds can be made by measuring the angle of the Cerenkov cone, like photographing ship wakes to measure ship speeds. A portion of the light emitted by the decelerated particle is coherent and is emitted at a characteristic angle



$$\cos\theta = \frac{c}{vn}$$

v = particle velocity
n = index of refraction of the medium

For water with n=1.33, the limiting angle for high speed particles is given by:

$$\theta = \cos^{-1}\frac{1}{1.33} = 41.2^\circ$$

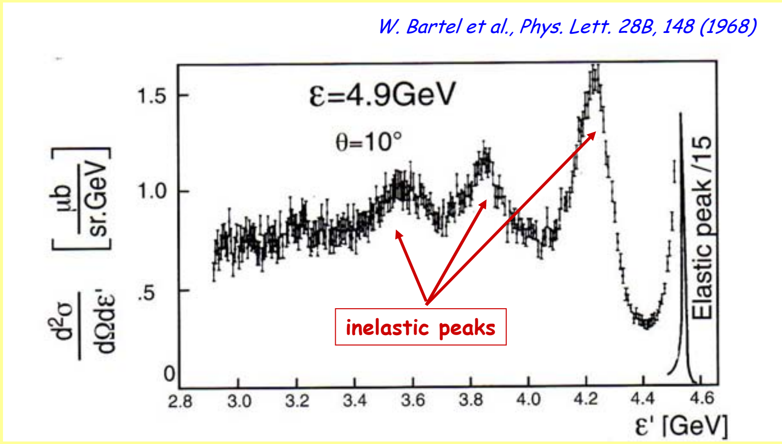
The threshold particle speed for Cerenkov radiation is v = c/n, which for an electron in water gives a threshold particle kinetic energy of 0.26 MeV.

Early Cerenkov detectors used glass, lucite and mica as detector media. They all had indices of refraction around n = 1.5, so the limiting Cerenkov angle was about 48 deg. Although the limiting Cerenkov radiation can be produced at all forward angles as the particle slows down, in practice the emission is seen as a narrow cone with only a few deg. width.

A practical application for electron scattering experiments is to use a Cerenkov detector in 'threshold' mode, where only particles of a certain minimum velocity will be detected. One can tune this minimum velocity to have the detector only fire for electrons, and not to fire when slower particles e.g. pions, muons, protons… pass through it. This offers efficient selection of the signal due to scattered electrons (fastest) against that which might otherwise be produced by background particles.

To obtain a lower index of refraction (higher velocity cutoff for a threshold detector), Cerenkov detectors are often made of very low density materials, e.g. a gas cell as in the previous slide, or 'aerogel', a very low density, semi transparent material made out of a silica foam.

What happens when we look at **protons** with a spectrometer like this? 17



We see **excited states**, but on a completely different energy scale!!

$\rightarrow$ What are these, what sets the energy scale, and why are the peaks so broad compared to ^{12}C ? (ANSWERS NEXT WEEK!)